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Performance Evaluation of a Real-Time Aerosol Monitor

By K. L. Williams and R. J. Timko

UNITED STATES DEPARTMENT OF THE INTERIOR

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cm	centimeter	m^3/min	cubic meter per minute
ft	foot	mg	milligram
ft^3/cm	cubic foot per minute	mg/m^3	milligram per cubic meter
ga	gauge	min	minute
gal	gallon	mm	millimeter
g/cm^3	gram per cubic centimeter	µm	micrometer
h	hour	pct	percent
L/min	liter per minute	yr	year

PERFORMANCE EVALUATION OF A REAL-TIME AEROSOL MONITOR

By K. L. Williams [1] and R. J. Timko [2]

ABSTRACT

The Bureau of Mines laboratory tested the response of a commercially available real-time aerosol monitor (GCA RAM-1) to various dusts. Monitor measurements were recorded, averaged, and compared with simultaneous gravimetric measurements of each test dust. Tests usually lasted several hours. The test dusts of various particle size distributions used included coal, limestone, and a commercially available test dust. For each particular dust, the monitor response was linear and correlated well with mass concentration over the range of about 0.5 to 10 mg/m^3.

The monitor can estimate a 2.0-mg/m^3 respirable coal dust concentration within as little as ±6 pct with 95 pct confidence. The monitor must, however, be calibrated with the dust to be measured because the instrument response is affected by the type of dust particle. The average monitor response to a mass concentration of coal dust was approximately twice the average monitor response to the same mass concentration of limestone dust.

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INTRODUCTION

In 1978, GCA Corp., Technology Div., Bedford, MA, designed and fabricated the RAM-1 for the Bureau of Mines under contract H0377092, "Improved Light Scattering Dust Monitor." This report describes the procedure and results of laboratory tests performed by the Bureau to evaluate the response of the RAM-1 to various dusts.

The RAM-1 measures respirable dust concentrations in the air almost instantaneously by using a light-scattering technique. A sampling pump draws air into a sensing chamber where it passes through the path of a light beam. Dust in the air scatters some of the light to a detector that produces an electrical signal proportional to the intensity of the light.

The intensity of light scattered from dust particles is a function of the particle size, shape, refractive index, wavelength of the light, and the angle from which the light is detected. It is not a function of the density of the particles, and thus is not a direct function of the mass of the particles.

However, the health hazards posed by various dusts in mines are related to the mass concentration of the particular dust. For that reason, GCA tried to design the RAM-1 to measure the mass concentration of dust, regardless of particle characteristics such as size, shape, or refractive index. GCA selected the design based on a dust monitor built earlier in the Federal Republic of Germany with similar characteristics. That monitor (the Tyndallometer TM-Digital) (1)[3] successfully reduced the dependence of light scattering on the characteristics of particles in coal mines.

The RAM-1, because of its fast response, could be used in many mining applications, especially for dust monitoring for control of respirable coal mine dust (2). Thus, the Bureau tested the response behavior of the instrument when measuring various test dusts. The RAM-1 was treated as a "black box;" no prior assumptions were made about response behavior. The questions were--

1. Is the instrument response linear with mass concentration?

2. Does the instrument respond differently to different dusts?

3. What is the estimate of precision for a given type of dust?

EQUIPMENT AND PROCEDURE

Both the RAM-1's and gravimetric dust sampling devices were exposed to various concentrations and particle size distributions of coal dust, limestone dust,[4] and Arizona Road Dust[5] (ARD).[6] A description of the equipment, test procedures, and rationale follows.

TEST CHAMBER

Figure 1 illustrates the test setup. The test dust was dispersed by feeding the dry dust into a 61- by 91- by 122-cm plywood chamber using either a Wright dust feeder or a TSI model 3400 fluidized bed aerosol generator (FBAG) (3). Although the FBAG characteristically produced a more constant dust concentration in the chamber, the Wright dust feeder was occasionally needed to obtain higher concentrations. Inside the chamber, a small fan was used to mix the dust and air.

[3] Underlined numbers in parentheses refer to items in the list of references preceding the appendixes.

[4] Typically called "rock dust," limestone dust is mixed with dust on surfaces inside coal mines to reduce flammability.

[5] Reference to specific products does not imply endorsement by the Bureau of Mines.

[6] ARD is a carefully sized, commercial test dust used primarily to test the efficiency of air filters for internal combustion engines.

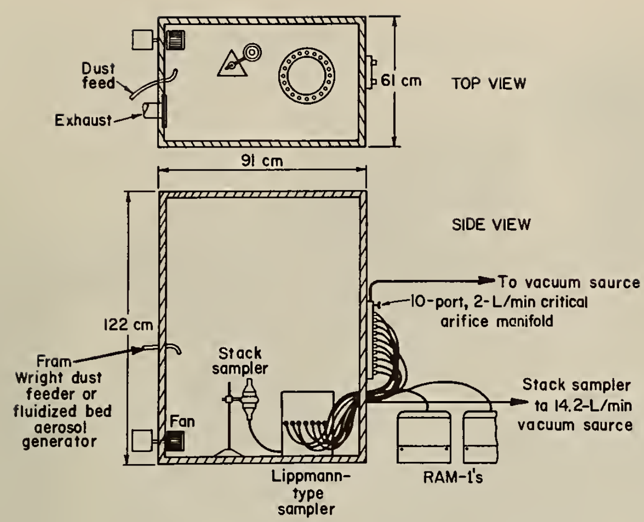

FIGURE 1. - Test setup.

LIPPMANN-TYPE SAMPLER ARRANGEMENT

Experience had indicated that the small fan ensured that no severe concentration gradients existed in the chamber--at least when measurements were averaged over several hours. Nevertheless, to assure that all dust sampling devices were exposed to as uniform a dust cloud as possible, a device patterned after the Lippmann sampler (4) was used.

The Lippmann-type sampler (fig. 2) was fabricated from a 5-gal metal can. Approximately 18 cm from the top, a round plexiglass platform was mounted in the can with 20 holes drilled equidistant at a 10-cm radius. Dorr-Oliver cyclones (5-6) (sampling heads) were placed in those holes with the inlets facing the center. A lid with a 5-cm-diam hole cut in the center was placed on top of the can.

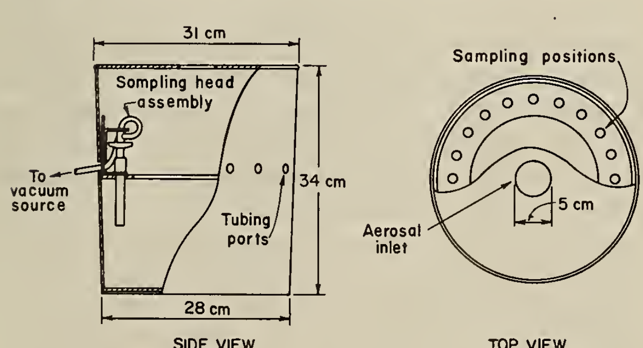

FIGURE 2. - Lippmann-type sampler.

Dusty air in the chamber entered the device through the hole in the lid and was drawn vertically downward toward the center of the plexiglass platform. Because all cyclones mounted in the platform operated at 2-L/min flow rate, the dust cloud was distributed evenly along each sampling cyclone. With this arrangement, the coefficient of variation among the 10 gravimetric sampling device measurements was almost always less than 10 pct.

GRAVIMETRIC SAMPLERS

Ten gravimetric sampling devices were used to make a reference measurement of the mass concentration of dust. Each gravimetric device consisted of a Mine Safety Appliance Co. (MSA) sampling head connected to a critical orifice (7) controlled airflow system. MSA sampling heads consist of Dorr-Oliver 10-mm-diam nylon cyclone particle size classifiers and preweighed 37-mm polyvinylchloride membrane filters in plastic filter cassettes. The cyclones retain the large, nonrespirable particles and allow respirable particles to pass through to the filters.

For the tests, critical orifices (CO's) were fabricated from 20-ga hypodermic needles. The orifices were calibrated to 2±0.01 L/min by shortening the needle or modifying the opening. A wet test meter was used to measure airflow through the CO's. Initially, flow rates were checked before and after each test. Later, because the CO's were quite stable, spot checks were relied on to assure a constant 2-L/min flow rate through the gravimetric devices.

The components for each gravimetric sampling device were labeled and always used together. That procedure helped in the location and correction of any equipment problems.

THE RAM-1

The RAM-1 (fig. 3) measures and displays current respirable dust levels in

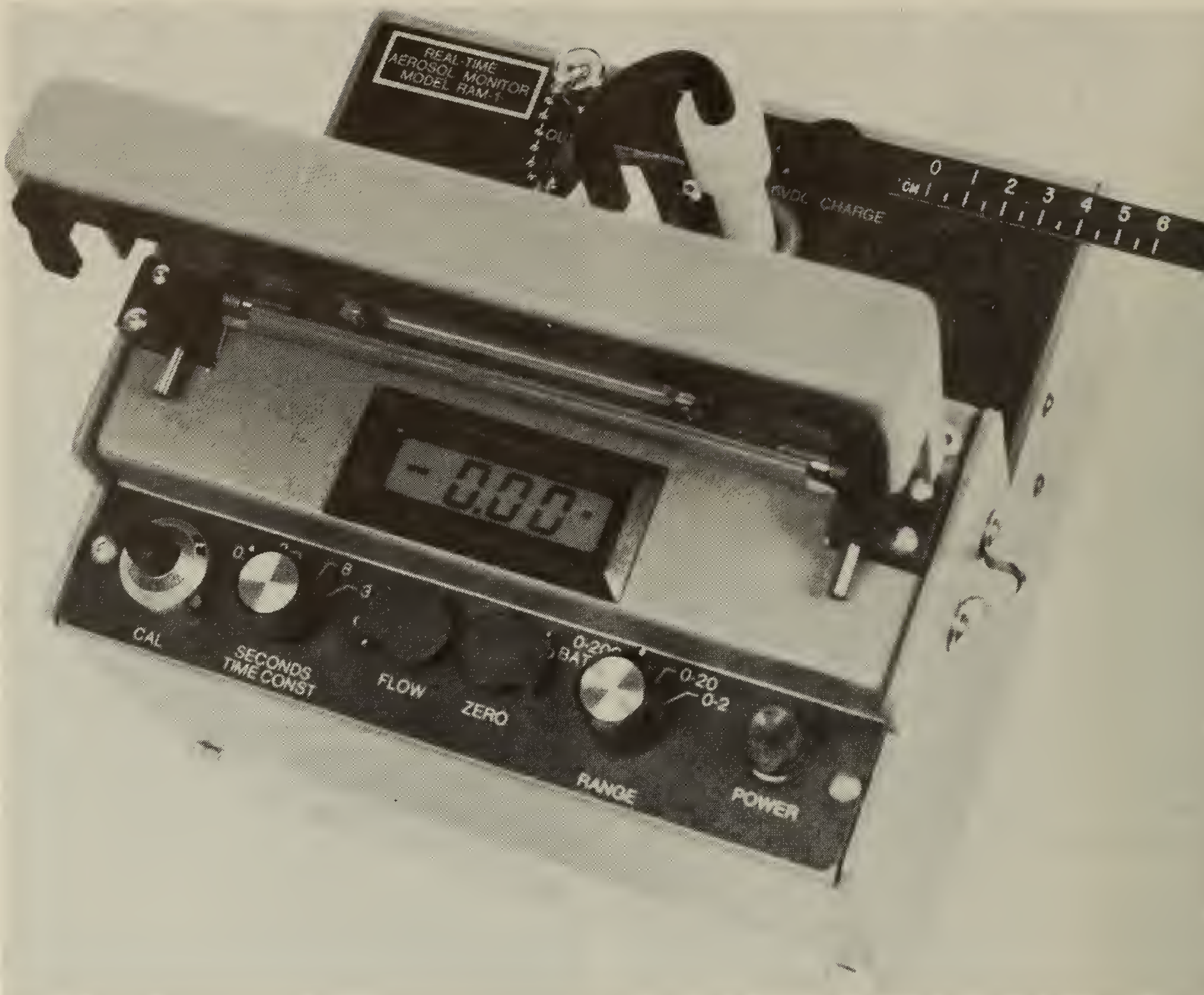

FIGURE 3. - Real-time aerosol monitor (RAM-1).

the air. The dusty air is drawn through a 10-mm-diam Dorr-Oliver nylon cyclone. Respirable dust (8), the portion of the sampled dust that passes through the cyclone, enters a light-scattering chamber. Here the instrument detects light scattered from the particles at an angle of 70°±25°. The detector converts the light into an electrical signal proportional to the amount of dust present in the airstream. A detailed description of the instrument design has been given in other reports (2, 9-10).

Circuitry is temperature compensated and protected against humidity. The Bureau extensively tested the electronic characteristics of the RAM-1 and found the instrument to be extremely stable. Those test results are discussed in the contract final report (9).

The RAM-1's also sampled from inside the Lippmann-type sampler. For the RAM-1's, MSA sampling heads were modified as follows (fig. 4). The fitting from the cyclone holding bracket normally used to connect the flexible tubing to the exit side of the filter cassette was removed. A short copper sleeve was inserted as a spacer between the top of the bracket and the top of the nylon cyclone. The spacer kept the cyclone vortex finder properly aligned and sealed to the cyclone body. Flexible tubing used to connect each RAM-1 to its sampling head was inserted

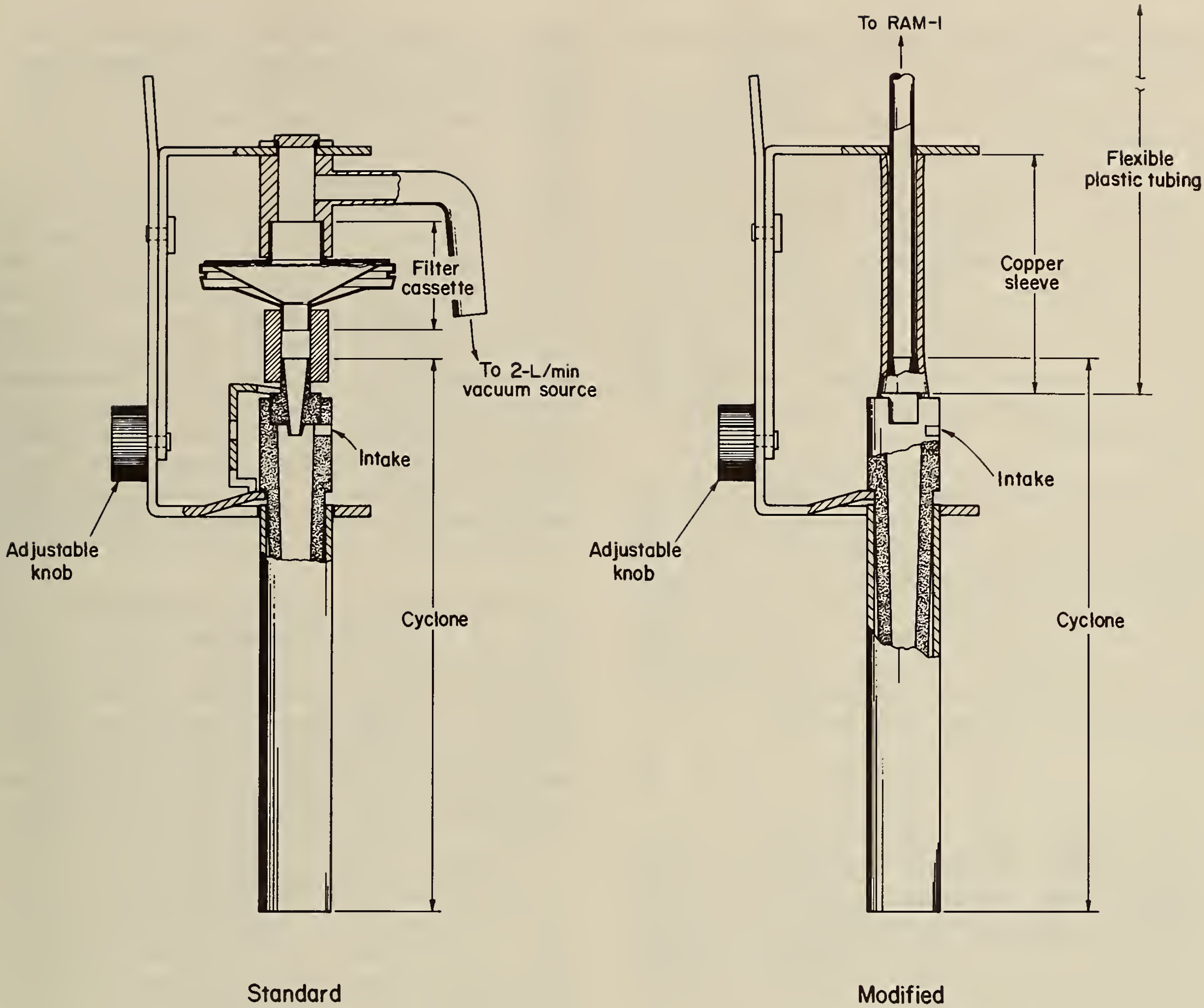

FIGURE 4. - Standard (left) and modified (right) cyclone arrangements.

through the top of the bracket, passed through the copper sleeve, and then was connected to the exit port of the cyclone.

Respirable dust passing through the cyclone flowed through the flexible tubing to the entry port of the RAM-1 located outside the chamber. Tubing between the sampling head and the RAM-1 units was limited to 3-ft lengths to minimize dust losses in the tubing.

TUBING DUST LOSSES

Dust losses can occur when transporting dusty air through tubing. Mounting of the cyclone on the RAM-1 inlet and placement of the entire instrument within the test chamber could reduce these losses. This was not done in the Bureau's tests; however, the test setup used was justified in two ways: First, such an arrangement allowed use of the Lippmann-type sampler so that all sampling heads were exposed to the same dust cloud[7] and, second, dust losses in the

[7]Because of the volume occupied by the bodies of the RAM-1's, the cyclone inlets could not be placed near enough to each other to ensure each instrument sampled the same dust atmosphere.

tubing were assumed to be about the same in all cases.

A short series of tests was performed to investigate the magnitude and constancy of dust losses in the tubing. A discussion of these tests and the results are given in appendix A. Briefly, dust losses in the tubing were less than 10 pct. Because the purpose of the evaluation was to compare responses of the RAM-1 to various dusts, not to calibrate the instruments to indicate an absolute value, that small constant bias was not troublesome.

However, dust losses were not constant. Variations in dust losses appear as random error of the RAM-1 measurements, causing the RAM-1 measurements to appear to be less precise. If the RAM-1 was operated with the cyclone mounted directly on the inlet, variable tubing losses would be eliminated, and the RAM-1 precision would be slightly higher.

TEST PROCEDURES

The RAM-1 units were operated from their battery chargers to avoid problems with battery discharge or failure. With the RAM-1 reference scatterer inserted into the light beam, the gain of each RAM-1 unit was adjusted so that the instrument indicated the calibration value recommended by the manufacturer. Before each test, the zero and gain were checked. It was found that adjustments to gain and zero were rarely needed.

Once the RAM-1 units and gravimetric sampling units were prepared, the dust generation system was started and allowed to stabilize. Determination of the dust concentration stabilization (usually after 1 h) was made by observing readings on the RAM-1 units. The flow system for the gravimetric sampling devices was then turned on and recording of the electrical output signal from the RAM-1 units on a strip chart recorder began. Tests lasted approximately 4 h, depending on the concentration of the test dust.

The objective when deciding test duration was to sample long enough to collect at least 1 mg of dust on the filters of the gravimetric sampling devices. The precision of the analytical balance for a single weighing was ±0.01 mg. Weighing precision, when considering preweighing and postweighing necessary to determine the mass of the collected dust, was then 0.014 mg. With a dust mass of at least 1 mg, relative weighing error attributable to the balance, neglecting any error introduced by the operator, was limited to 1.4 pct.

After the test, the area under the curve of each RAM-1 recorded output trace was calculated to determine the average reading over the test period. That reading was compared with the mean of the 10 gravimetric concentration measurements. The gravimetric concentration (Conc.) was determined using the following equation:

$$\text{Conc. (mg/m}^3\text{)} = \frac{\Delta m}{(0.002)\ (t)}, \qquad (1)$$

where Δm = mass of the dust collected on the filter, mg,

and t = sampling time, min.

The constant, 0.002, is the flow rate of the samplers in cubic meters per minute.

Periodically throughout the series of tests, the size distribution of the test dust was measured with an Andersen Mark III stack sampler. The Mark III is an eight-stage cascade impactor with stage size cutoffs ranging from 13.6 to 0.54 µm when operated at 14.2 L/min (0.5 ft³/min).

RESULTS AND DISCUSSION

The intensity of light scattered from dust particles is not a direct function of the mass of the particles. Light-scattering theory (12) states that the intensity of the light scattered by a particle will depend on such things as the wavelength of the source light, the angle between the incident and the

detected light, particle index of refraction, and particle size. It does not depend on particle density. Light-scattering behavior is fairly predictable for ideal spherical particles. However, in most situations, particle shape factors complicate the matter. Thus, the theory does not predict a direct functional relationship between the intensity of scattered light and the mass of the particle. Any correlation between the intensity of the scattered light and the mass concentration of dust is statistical rather than functional. No exact mathematical relationship exists that relates scattered light intensity to particle mass in all cases. For a more complete discussion of statistical versus functional relationships, see reference 13.

UNCERTAINTY IN THE GRAVIMETRIC MEASUREMENT

Figures 5 through 9 show the scatter plots and linear regressions of RAM-1 readings versus gravimetrically determined respirable dust concentrations. Each data pair (x, y) represents the RAM-1 reading averaged over the time of one test (y value) and the mean of 10 gravimetric measurements obtained during the same time period (x value).

The root-mean-square estimated relative standard deviation of the gravimetric measurements ($\overline{RSD}$) for all tests is 0.11. This value was calculated as follows:

$$\overline{RSD} = \left[\frac{1}{N} \sum (S_i/\bar{X}_i)^2 \right]^{1/2}, \qquad (2)$$

where N = the number of tests,

S_i = the estimated standard deviation of the gravimetric measurements for the ith test,

and $\bar{X}_i$ = the mean of the gravimetric measurements for the ith test.

Obviously, not every test exhibits a RSD of exactly 0.11; however, this root-mean-square average could roughly indicate the expected uncertainty in a single measurement made by one gravimetric sampler.

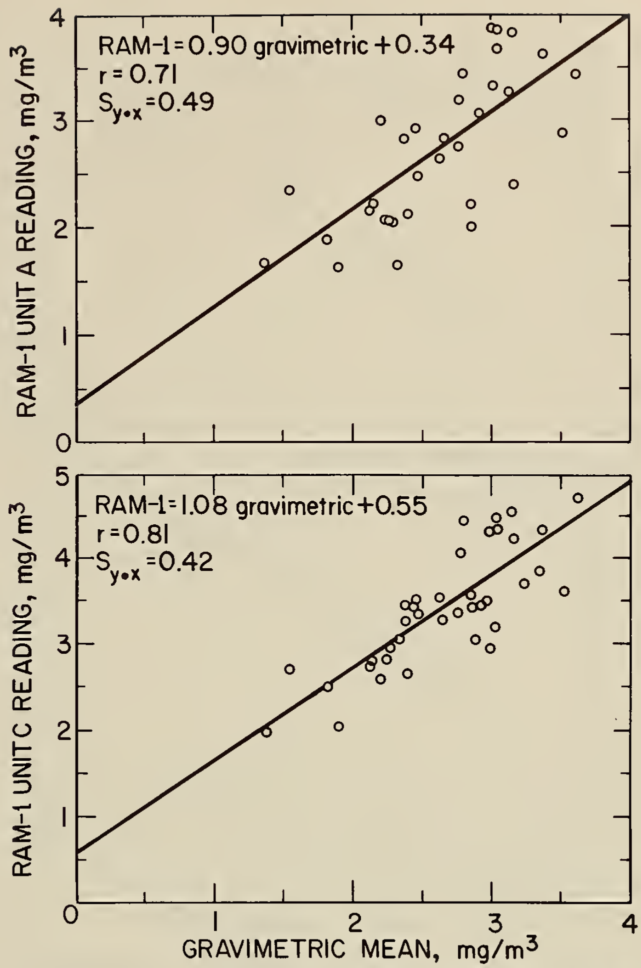

FIGURE 5. - Comparison of respirable dust concentrations measured by RAM-1 with concentrations measured gravimetrically for coal 1.

The independent variable plotted in figures 5 through 9, however, is not a single gravimetric measurement. Instead, the mean ($\bar{X}$) of *10* such measurements was used to estimate the mass concentration. To determine how well this mean estimates the true concentration of dust (μ_0) as measured by gravimetric samplers, the following expression is used:

$$\mu_0 = \bar{X} \pm t_{(\nu,\alpha)} \frac{S}{\sqrt{n}}, \qquad (3)$$

where $\nu = n-1$ = degrees of freedom,

n = number of samples,

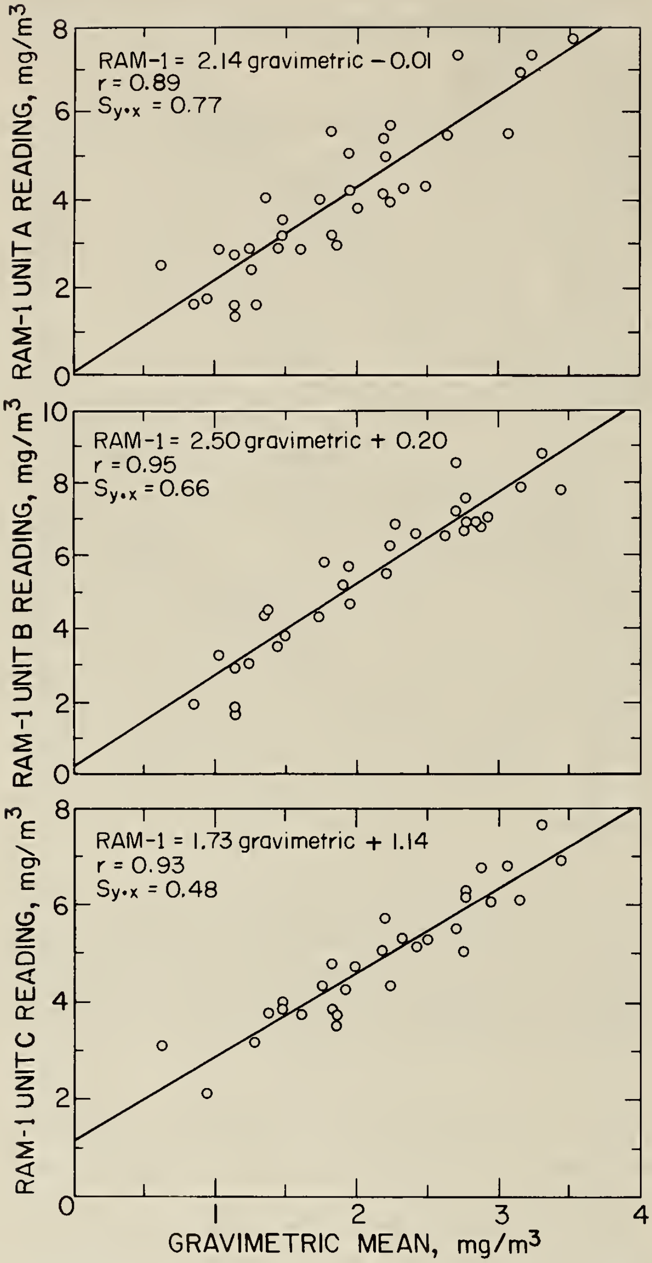

FIGURE 6. - Comparison of respirable dust concentrations measured by RAM-1 with concentrations measured gravimetrically for coal 2.

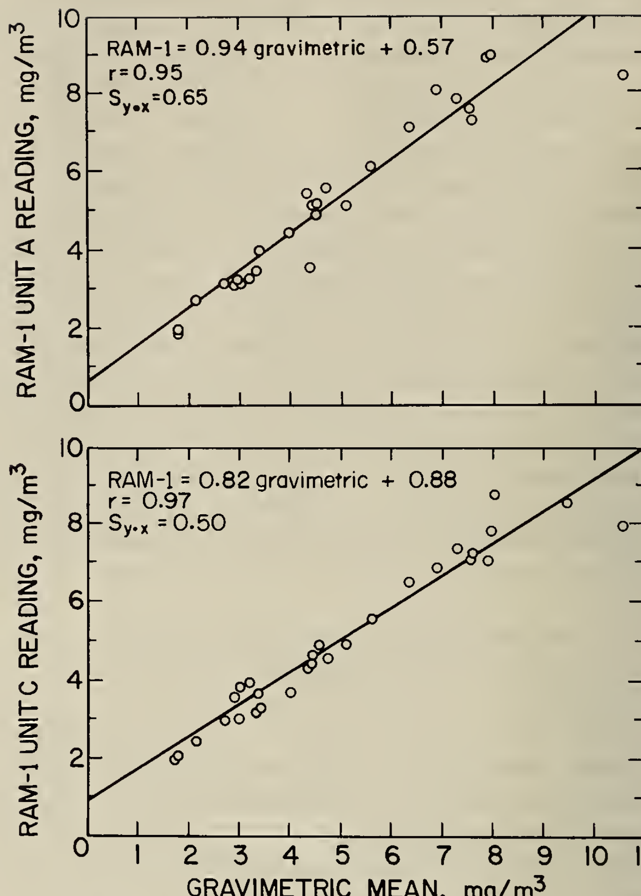

FIGURE 7. - Comparison of respirable dust concentrations measured by RAM-1 with concentrations measured gravimetrically for Arizona Road Dust.

$1-\alpha$ = confidence level,

and S = estimated standard deviation of the samples.

In this case, $n = 10$ and $\nu = 9$. From a table of values for $t_{(\nu,\alpha)}$, it is found that for a confidence level of 95 pct, $t_{(9,\ 0.05)} = 2.262$.

As an example, calculate the 95-pct confidence interval for the true concentration using equation 3 when the sample mean ($\bar{X}$) is equal to 2.0 mg/m^3. If RSD = 0.11, then a likely estimated standard deviation (S) would be 0.22, since $S = (RSD)\bar{X} = (0.11)(2.0)$. Substituting into equation 3 shows $\mu_0 = 2.0 \pm 0.16$ mg/m^3 ~ 2 mg/m^3 ±8 pct. In other words, if the mean of 10 gravimetric mass measurements for a particular test is 2.0 and the estimated standard deviation of one measurement is 0.22, then a 95-pct assurance exists that the true concentration in the

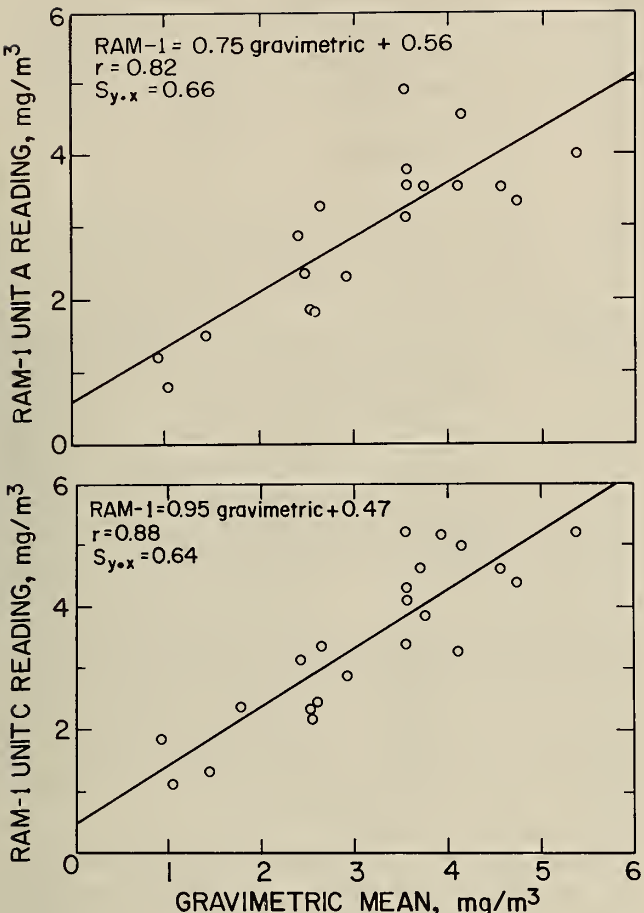

FIGURE 8. - Comparison of respirable dust concentrations measured by RAM-1 with concentrations measured gravimetrically for limestone 1.

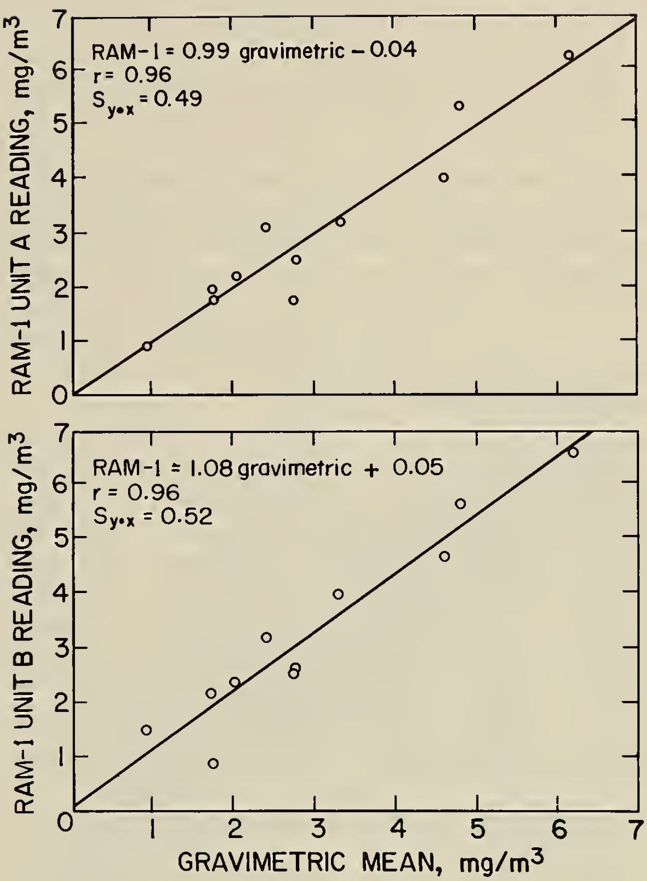

FIGURE 9. - Comparison of respirable dust concentrations measured by RAM-1 with concentrations measured gravimetrically for limestone 2.

test chamber as measured by the reference method is within the interval of 2 mg/m^3 ±8 pct.

Normally, the independent variable in a regression analysis is defined to be without uncertainty. From the preceding discussion it can be seen that if the gravimetric mean ($\bar{X}$) is used to estimate the dust concentration in the test chamber, the uncertainty is not excessive. Therefore, it is assumed that using $\bar{X}$ as the independent variable in the regression analysis is at least reasonable.

Note, however, that any estimate of uncertainty in the RAM-1 measurements will be inflated by the uncertainty in the gravimetric reference measurement and result in an underestimation of the true precision of the RAM-1.

LINEARITY OF RAM-1 RESPONSE

By visually reviewing the plots in figures 5 through 9, it was concluded that the response of the RAM-1 is linear with respect to mass concentration for each test dust. To verify that conclusion, a statistical randomness test was applied to examine linearity (11). Briefly, the sequence of signs (+ or -) of the deviations of the measured y values (RAM-1 responses) from the corresponding fitted regression line values in order of increasing x values (mean gravimetric measurement), was considered. The following were determined with this information: (a) the number of "+" signs, (b) the number of "-" signs, and (c) the number of runs. A run is defined as an uninterrupted series of one or more of the same sign. Values a and b were used as

parameters in a table of critical values for runs. If the observed number of runs was within the two limiting table values, then the null hypothesis of linearity could not be rejected at the significance level of the table elected for use.

The randomness test for linearity was performed on each of the plots in figures 5 through 9. In no instance, at a significance level of 0.05, could the null hypothesis of linearity be rejected; that is, it could not be denied that the response of the RAM-1 to the various test dusts was linear.

There are better tests for linearity than the above randomness test; however, most require that there be more than one observed RAM-1 reading (y value) for each corresponding dust level (x value). Unfortunately the dust generation system used in this evaluation could not exactly repeat dust concentrations from day to day to allow repeated RAM-1 readings to be made of identical dust concentrations.

EFFECT OF PARTICLE CHARACTERISTICS

The next question addressed is whether or not the RAM-1 responds differently to different dusts. To do so, the values for the slope of the regression of the RAM-1 versus gravimetric readings for each type of dust are compared. The slope characterizes the instrument response well if the response is linear and if the correlation between RAM-1 readings and gravimetric measurements is high. It has already been demonstrated that the RAM-1 response is linear with mass concentration; now the degree of correlation between the RAM-1 and gravimetric readings will be examined.

Table 1 shows the values for the slopes, correlation coefficients, and standard deviation of regressions (standard error of estimate) from the linear regression analyses for figures 5 through 9. The regression equation is

$$y = mx + b \tag{4}$$

where y = RAM-1 reading, mg/m^3,

x = mean gravimetric reading, mg/m^3,

m = regression slope,

and b = y axis intercept, mg/m^3.

TABLE 1. - Regression statistics

RAM-1	Coal		ARD	Limestone	
	1	2		1	2
REGRESSION SLOPES					
A..........	0.90	2.14	0.94	0.75	0.99
B..........	(1)	2.50	(1)	(1)	1.08
C..........	1.08	1.73	.82	.95	(1)
CORRELATION COEFFICIENTS					
A..........	0.71	0.89	0.95	0.82	0.96
B..........	(1)	.95	(1)	(1)	.96
C..........	.81	.93	.97	.88	(1)
STANDARD DEVIATION OF REGRESSION					
A..........	0.49	0.77	0.65	0.66	0.49
B..........	(1)	.66	(1)	(1)	.52
C..........	.42	.48	.50	.64	(1)

[1]Unit was not available.

The sample correlation coefficient (r) is an estimate of the true correlation coefficient (ρ) which is the degree of association between the y and x values in a statistical relationship. The values of r in table 1 range from 0.71 (a fair correlation) to 0.97 (a high correlation), with a test case average of r = 0.89. In general then, the light-scattering signal from the RAM-1 correlates well with mass concentration—at least when dust parameters such as size, index of refraction, density, and shape are held constant.

Because the RAM-1 response is linear and correlates well with gravimetric measurements of mass concentration, the slopes of the regression lines can be reasonably interpreted as the response of the RAM-1 to a particular dust. The slopes can be used to compare the RAM-1 response to different test dusts. Table 1 lists the regression slopes for each RAM-1 unit and for each test dust. Except for coal 2 cases, the regression

slopes center around 0.9, ranging from 0.75 to 1.08. The regression slopes for the tests with coal 2, however, are noticeably higher--roughly by a factor of 2. This difference is shown in figure 10.

Because of data scatter, regression analysis provides only an estimate of the true regression; that is, some uncertainty exists about the true slope and intercept of the regression line. The uncertainty is a function of the extent of the scatter.

Each regression in figure 10 has an associated uncertainty. Does the data scatter around the regression lines in figure 10 nullify the apparent differences among the slopes? The standard estimate of error ($S_{y.x}$) for the sample is a measure of the data scatter around the calculated regression line. If the calculated regression is a good estimate of the true relationship between the RAM-1 values and the mass concentration values, then $S_{y.x}$ is a good estimate of $\sigma_{y.x}$, the true standard estimate of error. By definition, 68 pct of data pairs should lie within the values of $\pm\sigma_{y.x}$.

In figure 10, the gray shaded intervals surrounding the regression lines represent $S_{y.x}$. For test dusts other than coal 2, individual $S_{y.x}$ intervals overlap to a great extent; the larger shaded area in figure 10, about the regression lines, represent the outermost bounds of all the overlapping $S_{y.x}$ intervals. The $S_{y.x}$ interval for coal 2 does not overlap the others for concentrations greater than 1 or 2 mg/m^3. Although more rigorous tests could show the same results mathematically, this simple analysis graphically illustrates that the response of the RAM-1 to coal 2 is different than its response to the other dusts. The results for coal 2 are real: The behavior was verified by repeating tests.

Efforts were then made to discover why the RAM-1 responded so differently to coal 2 than to coal 1 and the other dusts. What was different about coal 2? The characteristics to be considered are size, density, shape, and surface properties.

Size or Density

Table 2 lists size distribution and density data for the test dusts. The values for density (ρ_0) were not measured, but were taken from the literature. The mass median aerodynamic diameters (MMAD) and geometric standard

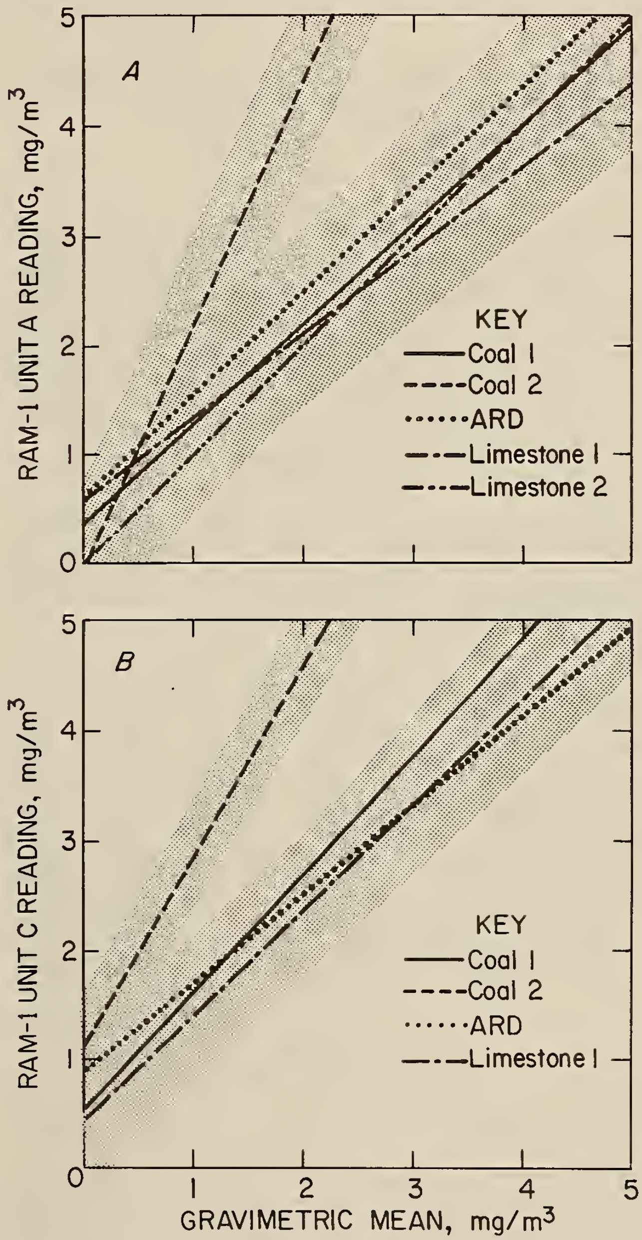

FIGURE 10. - Response of RAM-1 to coal 1, coal 2, limestone 1, limestone 2, and Arizona Road Dust. Shaded intervals show $S_{y.x}$.

deviations (σ_g) were measured using an Anderson Mark III stack sampler cascade impactor. These table values for particle size represent the average of various measurements made throughout the test program.

TABLE 2. - Dust parameters

Dust	MMAD,[1] µm	σ_g,[2] µm	ρ_0,[3] g/cm^3
Coal 1..............	3.5	2.0	1.3
Coal 2..............	3.6	2.7	1.3
ARD.................	1.3	2.8	2.6
Limestone 1.........	1.6	3.8	2.7
Limestone 2.........	.5	5.4	2.7

[1]Mass median aerodynamic diameter.
[2]Geometric standard deviation.
[3]Particle density.

To determine the MMAD and σ_g, the cumulative mass percentage collected on each impactor stage was calculated. These values were plotted on log-probit scale paper against the aerodynamic cut diameter for each stage. The data in all cases approximated a straight line implying that the particle sizes were lognormally distributed. A computer was used to plot the size data, to calculate a linear regression, and to identify the MMAD and σ_g based on the regression analysis.

From table 2, it can be seen that the MMAD for coal 1 and 2 are nearly the same, but that σ_g is 2.0 for coal 1 and 2.7 for coal 2. It was thought perhaps this difference in size distribution parameters was responsible for the large difference in RAM-1 response between coal 1 and coal 2. If so, a proportional response difference between limestone 1 and limestone 2[8] could also be expected.

The size distribution differences between limestone 1 (MMAD = 1.6 µm, σ_g = 3.8) and limestone 2 (MMAD = 0.5 µm, σ_g = 5.4) are greater than between coal 1 and coal 2. Accordingly, the RAM-1 response difference between limestone 1 and limestone 2 would be expected to be even greater than between coal 1 and coal 2. In fact, however, the regression slope is 0.75 for limestone 1 and 0.99 for limestone 2--much less than the response difference between coal 1 and coal 2. Indeed, particle size may be somewhat responsible for these differences in response; however, particle size cannot solely account for the large response difference between coal 1 and coal 2.

Shape Factor

Assuming that particle size parameters are not the dominant cause of the RAM-1 response difference between coal 1 and coal 2, other possibilities were investigated. Figures 11 and 12 are scanning electron microscope micrographs of coal 1 and coal 2. The micrographs were compared and no marked differences in particle shape were seen. A stereoviewer was used to look at the dust particles in three dimensions to see if perhaps the particles in one sample tended to be

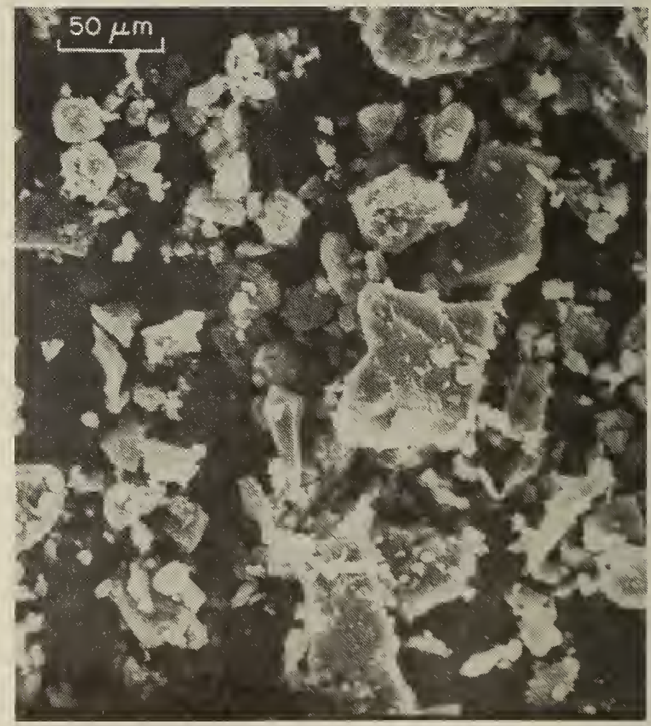

FIGURE 11. - Scanning electron microscope micrograph of coal 1 (X 300).

[8]Limestone 2 was generated by passing limestone 1 through a cyclone size classifier (D_{50} = 3.5 µm) before feeding it into the test chamber.

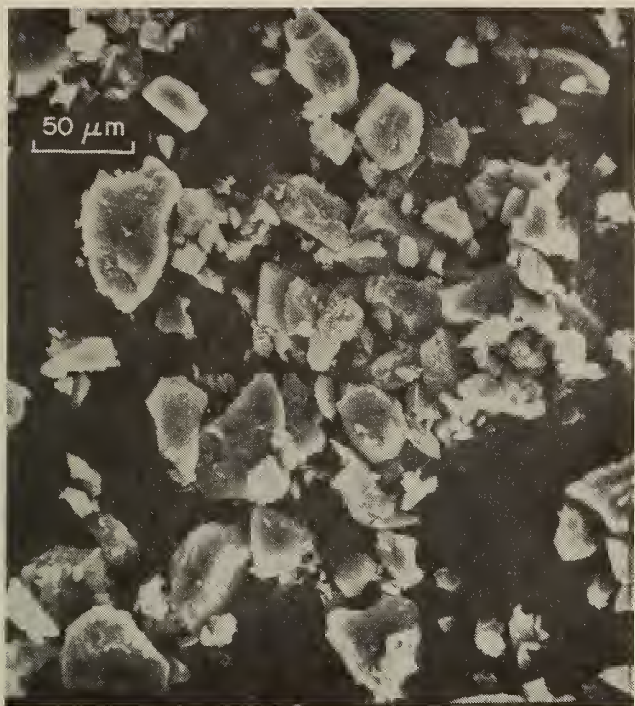

FIGURE 12. - Scanning electron microscope micrograph of coal 2 (X 300).

flatter than the particles in the other sample. Here again, the two coal dust samples were indistinguishable.

Surface Properties

Finally, the coal dust samples were examined with an optical microscope at a magnification of X 105 using white light to illuminate the sample. Two individual observers described coal 2 as "sparkling" much more than coal 1; that is, the surfaces of coal 2 appeared to be more highly reflective.

One hypothesis is that some type of surface degradation had occurred during the 1- to 2-yr storage time for coal 1, dulling the surface of the particles. Coal 2 on the other hand, had been freshly prepared. If this hypothesis is true, dust from freshly mined coal should be more like coal 2.

Although surface reflectance appears to be a dominant cause of the difference between the RAM-1 responses for coal 1 and coal 2, particle size cannot be eliminated as a potential cause of response variations. Response characteristics are likely to be a function of the combination of size, surface reflectance, and index of refraction. For example, the effect of size may be greater for highly reflective particles such as coal; whereas the effect of size may be diminished for more nonreflective particles such as ARD or limestone. To resolve such issues is difficult, largely because of the difficulty in repeatedly generating particles with known characteristics.

While the observed phenomenon is difficult to explain, the important facts are that the response of the RAM-1 to different dusts can indeed be different and that the RAM-1 response is constant (precise and linear with mass concentration) for consistent dust. Thus, the RAM-1, as with all light-scattering devices, must be calibrated with the dust to be measured if the user wishes to accurately estimate mass concentrations.

Calibration

To calibrate any instrument, one must assume that a strong, well-defined correlation exists between the phenomenon to be measured and the response of the instrument. The evidence presented to this point indicates that if the parameters of the test dust are held constant, the RAM-1 response is fairly well represented by a linear function of mass concentration. Therefore, the RAM-1 can be calibrated to indicate mass concentrations of dusts as long as the particle characteristics pertinent to light scattering do not change. Recommendations on the calibration of the RAM-1 are discussed in appendix B.

RAM-1 PRECISION

The final question to be addressed in this report is "How reproducibly can the RAM-1, once calibrated, predict the true mass concentration?" To answer this question, the 95-pct confidence interval about the linear regression line will be

determined and expressed as a percentage of the value of dust concentration predicted by the regression equation for a selected RAM-1 reading.

But first, the regression values listed in table 1 result from a regression of y on x; that is, RAM-1 values on gravimetric values. The form of the regression equation is

$$y_{(RAM-1)} = mx_{(grav)} + b. \qquad (5)$$

This equation is used to estimate what the RAM-1 might read when exposed to a particular mass concentration (x). Normally, however, a user obtains a reading with the RAM-1 and from that estimates the true mass concentration.

Generally, when a relationship is statistical in nature, a regression equation cannot be algebraically inverted. Specifically, since the correlation coefficient $|r| \neq 1$ for the relationship between the RAM-1 reading and the mass concentration,

$$x_{(grav)} \neq \frac{y_{(RAM-1)} - b}{m}. \qquad (6)$$

Thus, the regression analysis must be redone after reversing the x and y values. That way, the regression analysis will minimize the error in the predicted value of mass concentration for a particular reading on the RAM-1. The new regression equation is in the form

$$y_{(grav)} = m' \, x_{(RAM-1)} + b', \qquad (7)$$

where $m' \neq m$

and $b' \neq b$

unless $|r| = |r'| = 1.$

The mass concentration predicted by the new regression equation at a particular RAM-1 reading is the mean of a normal distribution of possible mass concentration values. That mean represents the true mass concentration only to the extent that the regression line represents the true relationship between the mass concentration and the RAM-1 response.

The regressions were recalculated using equation 7. The 95-pct confidence intervals (W_1) for the regression lines were calculated using the equation

$$W_1 = \sqrt{2F} \, s_y \left[\frac{1}{n} + \frac{(x_i - \bar{x})^2}{S_{xx}} \right]^{1/2}, \qquad (8)$$

where $s_y = \left[\dfrac{S_{yy} - (S_{xy})^2/S_{xx}}{n - 2} \right]^{1/2}$

$S_{yy} = \sum (y_i - \bar{y})^2,$

$S_{xx} = \sum (x_i - \bar{x})^2,$

$S_{xy} = \sum [(x_i - \bar{x})(y_i - \bar{y})],$

$\bar{x} = \frac{1}{n} \sum x_i,$

n = number of points,

x_i = value of x at which W_1 is calculated,

and F = table value for percentiles of F distribution.

Note: For the tests, $F = F_{0.95}(2, n - 2)$.

Then, for each RAM-1 unit and dust type, the 95-pct confidence interval at the predicted value of 2.0 mg/m^3 was determined as a percentage of that value (2.0). The intervals were examined at the predicted value of 2.0 mg/m^3 because the value 2.0 is fairly well centered in the range of data used in the regression analysis. Those percentages are listed in table 3.

An example to illustrate the significance of these results is as follows: Based on the value in table 3 for coal 2, whenever RAM-1, unit A, reads 4.35 mg/m^3, the true mass concentration calculated using the regression equation will be 2.0 mg/m^3 ±7.1 pct, 95 pct of the time. Note

TABLE 3. - Ninety-five-percent confidence intervals at Yc[1] = 2.0 mg/m^3, percent

RAM-1 unit	Coal		ARD	Limestone	
	1	2		1	2
A..........	16.6	7.1	27.2	34.2	25.4
B..........	([2])	5.7	([2])	([2])	24.8
C..........	12.1	6.4	24.0	25.2	([2])
Av.[3]....	36	33	28	20	11

[1]Predicted RAM-1 reading from regression analysis.
[2]Unit was not available.
[3]Not all RAM-1 units were available for each test; therefore, these values are the average number of tests for each dust type.

that one could vary the gain of the instrument so that the regression slope m' = 1. If in that case the interval W_1 remained the same, then when RAM-1, unit A, read 2.0, the true mass concentration would be 2.0 mg/m^3 ±7.1 pct, 95 times out of 100.

The analysis using equation 8 results in an interval (W_1) about predicted y values (gravimetric readings) that is valid for any and all x values (RAM-1 readings) in the range of data collected. Other methods are available to estimate the confidence interval for a single point on the line, but intervals calculated for a single point on a line are valid only for that point. The W_1's obtained from equation 8 are conservative estimate of the confidence of prediction because they are larger than intervals calculated about y for a single value of x by the ratio $\sqrt{2F}/t$. As stated in reference 13, "This wider interval (W_1) is the 'price' we pay for making joint statements about y for any number of or for all of the x values, rather than the y for a single x."

CONCLUSIONS

For specific dusts whose particle characteristics do not change significantly--

1. The RAM-1 response is linear with mass concentration. Thus, if dust particle characteristics are expected to be reasonably constant, the RAM-1 can confidently be used to evaluate dust control techniques where relative rather than absolute measurements are sufficient.

2. RAM-1 readings correlate well with mass concentration. Thus, a functional relationship can be derived between the RAM-1 output and mass concentration to calibrate the instrument for a particular dust. One might also adjust the gain of the instrument so that the RAM-1 directly indicates the mass concentration, but the gain setting would be different for different dusts.

3. The precision of the instrument (that is, its ability to reproducibly estimate the true mass concentration) is good, probably on the order of presently used gravimetric devices. Note that this precision estimate is for cumulative RAM-1 measurements made over periods greater than 4 h. The 95-pct confidence interval at 2.0 mg/m^3 ranged from about ±6 pct for coal 2 to around ±30 pct for limestone 1. The percentages calculated for limestone 1 and 2 were higher because fewer data points were available for the statistical analysis.

The estimates of precision presented here are conservative. Some of the errors attributed to the RAM-1 actually resulted from random dust losses in tubing (see appendix A). When the RAM-1 is used with the cyclone attached immediately before the sensing chamber (no tubing), the error caused by random dust losses in the tubing would be eliminated.

4. The response of the RAM-1, as with all light-scattering devices, is dependent on the characteristics of the dust being measured. It is emphasized that if the users wish to estimate the true mass concentration, they must calibrate the instrument with the dust to be measured.

RECOMMENDATIONS

The RAM-1 should be field tested in a wide variety of environments. The RAM-1 performs predictably well when exposed to laboratory generated dusts, but the response is affected by particle characteristics. Sufficient data regarding the range and frequency of particle characteristic variation in field environments are not available. Such data would allow the user to predict the effect on RAM-1 measurements of mass concentrations.

Work done by Tomb and Gero (14) indicated that in underground coal mines, the precision of long-term (>4 h) RAM-1 measurements is equal to or better than that of gravimetric personal samplers, and that once calibrated, the instrument read within ±10 pct of the gravimetrically determined mass concentration. Work of that type should continue to determine the limitations of the instrument when used in the field.

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APPENDIX A.--DUST LOSSES IN TUBING

The standard procedure used for determining the response of the RAM-1 to various dusts involved comparing RAM-1 measurements with gravimetric measurements. For the gravimetric samples, the respirable dust that exits the cyclone deposits immediately on a filter. For the RAM-1, however, respirable dust that exits the cyclone must travel through approximately 3 ft of flexible tubing before reaching the light-scattering sensing chamber. The following tests were performed to examine possible dust losses in the flexible tubing during transport.

EXPERIMENTAL PROCEDURE

Of the 10 gravimetric samplers normally used to determine the mean mass concentration of dust inside the dust chamber, five were modified to be like the ones used in the RAM-1 sampling train (see figure 4 in the main text). The filter cassette immediately atop the cyclone was removed and the flexible tube was attached directly to the exit port of the cyclone. The filter was reinserted into the sampling line approximately 3 ft downstream. In these modified gravimetric systems, therefore, respirable dust traveled through the same length of flexible tubing as in the RAM-1 sampling train before being collected on the filter.

Measurements made using the standard gravimetric sampling trains were designated as "inside" measurements since the filter cassette was located inside the Lippmann-type sampling arrangement with the cyclone. Measurements made using the modified gravimetric sampling trains were designated as "outside" measurements since the filter cassette was located outside the test chamber.

EFFECT ON BIAS

The mean of the five outside gravimetric measurements were compared with the mean of the five inside gravimetric measurements. The scatter plot and linear regression are shown in figure A-1. At first glance, the slope of 1.09 is disturbing since this would imply that dust is not lost in the tubing, but rather is created! However, a regression line is only an estimate of the true relationship. One can test the significance of the results in the following way (7).[1]

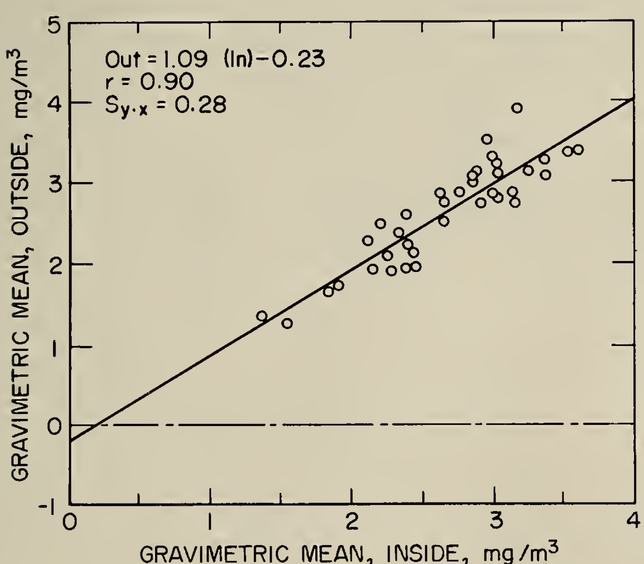

FIGURE A-1. - Comparison of respirable dust concentrations measured with filters inside the dust chamber (no tubing) with concentrations measured with filters outside the dust chamber (approximately 3 ft of tubing).

A null hypothesis that the true slope of regression (M) is equal to 1 (that is, no dust is lost in the tubing) is stated. A value, t, can be calculated using the following equation:

$$t = \frac{m - M}{S_m} \qquad \text{(A-1)}$$

where m = the slope of the regression estimate,

M = the slope of the true regression,

and S_m = estimated standard deviation of the value m.

[1] Underlined numbers in parentheses refer to items in the list of references preceding this appendix.

From the regression analysis, $m = 1.09$, $S_m = 0.086$, and $M = 1$ is selected arbitrarily. Substituting into equation A-1, $t = 1.05$. This t value is compared with a t distribution table value $t_{(\alpha/2,\ n-2)}$ where α is the significance level and n is the number of tests. In the reported case, $\alpha = 0.05$ and $n = 39$ were selected. The table value $t_{(0.025,\ 37)} = 2.03$. Now since $t \ngtr t_{(\alpha/2,\ n-2)}$, the null hypothesis cannot be rejected at the 0.05 significance level; that is, there is no statistically based reason to conclude that M is *not* equal to 1. Based on the data, it cannot be stated with any certainty that dust is lost in the tubing.

The confidence interval for M is given by

$$M = m \pm t_{(\alpha/2,\ n-2)}(S_m). \quad \text{(A-2)}$$

Substituting into equation A-2, $M = 1.09 \pm 0.17$ or $0.91 < M < 1.26$.

From the physics of the situation, $M > 1$ would not be expected because the tubing cannot create dust. However, dust *losses* in the tubing could be expected to be less than 10 pct, 95 times out of 100.

The preceding discussion deals with dust losses, or biases (systematic errors) in the comparison of RAM-1 readings with gravimetric readings. Such biases could be important when calibrating the RAM-1 to indicate mass concentration as determined by gravimetric devices. However, since the tests were to examine response behavior, this bias, if consistent, is not significant. What must be determined, however, is whether transporting the dust through the tubing introduces more *random* error. Since the same lengths of tubing are used in the RAM-1 sampling trains, any random error introduced by dust losses in the tubing would appear as less precision in the RAM-1 measurement.

EFFECT ON PRECISION

In figure A-2, the amount of data scatter about the estimated regression line is higher when the RAM-1 measurements are compared with gravimetric measurements made through a length of tubing (outside) than when the RAM-1 measurements are compared with gravimetric measurements made immediately after the cyclone (inside). $S_{y.x}$ is an estimate of the data scatter about the regression line. For RAM-1, unit C, $S_{y.x}$ increased from 0.42 to 0.55, or by 31 pct. For RAM-1, unit A, $S_{y.x}$ increased from 0.49 to 0.58, or by 18 pct. On the average, the random error introduced by drawing the dust through the tubing caused a 24-pct increase in the value of $S_{y.x}$. Therefore, one can safely assume that some of the scatter about estimated regression lines for RAM-1 measurements (all drawn through tubing) compared with gravimetric measurements made inside the dust chamber (no tubing) is due to random dust losses in the tubing to the RAM-1, in addition to that random measurement error inherent in the RAM-1. If this indeed is true, the estimates of the ability of the RAM-1 to reproducibly predict the true mass concentration are conservative.

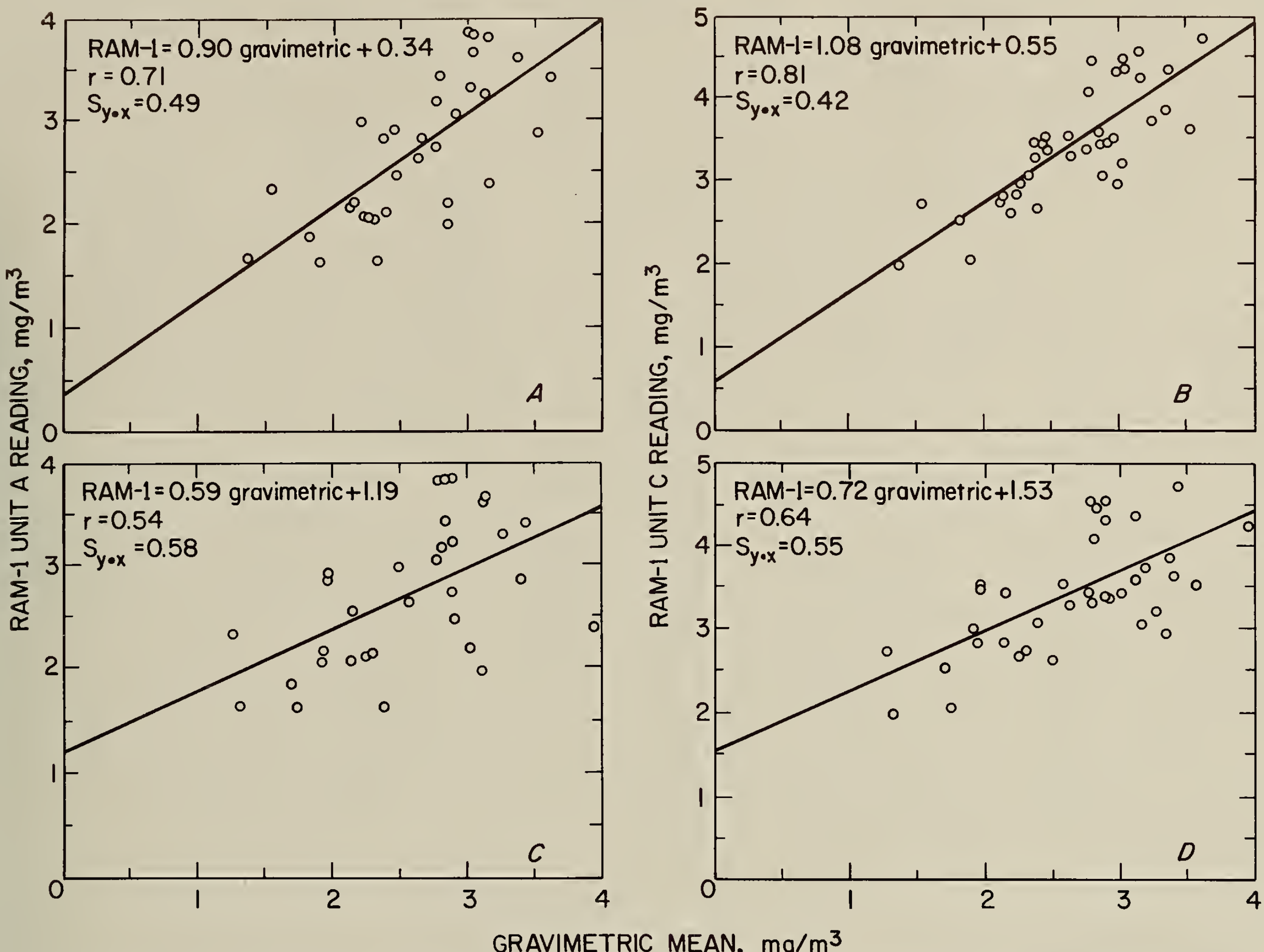

FIGURE A-2. - Comparison of respirable coal dust concentrations measured by RAM-1 with concentrations measured gravimetrically inside (*A*, *B*) and outside (*C*, *D*) the dust chamber.

APPENDIX B.--RECOMMENDATIONS ON THE CALIBRATION OF THE RAM-1

Previous Bureau work showed that the zero and gain of the RAM-1 are exceptionally stable (9). These tests have shown that for a given test dust, the RAM-1 response is linear and correlates well with mass concentration. Based on these findings, one can reasonably expect that--

1. The RAM-1 can be calibrated to indicate respirable mass concentrations directly in milligrams per cubic meter.

2. The RAM-1 must be calibrated for each type of dust to be measured.

Once calibrated, the reliability of subsequent measurements will then depend on the variability of the properties of the particles in the dust cloud.

To calibrate the RAM-1, the user must compare RAM-1 and gravimetric measurements as was done in these tests. The user can then either adjust the gain of the RAM-1 so that the instrument displays the proper concentration values, or develop a calibration curve to convert displayed values to the true mass concentration.

TUBING LOSSES

In either case, the user should be aware that some dust losses can occur if the dust is transported through long lengths of flexible tubing (see appendix A). Since the intent of this evaluation was only to observe response behavior, systematic losses were not important. However, if the user wishes to use the RAM-1 to obtain absolute values of dust concentrations, he or she should calibrate the instrument in the configuration in which it will later be used. In other words, if the application of the instrument will require that the sampled dust be drawn through tubing to the RAM-1 sensor, then the instrument should be calibrated using tubing of the same approximate length and material. That procedure will at least reduce bias in the measurements although the precision may still be measurably reduced.

DEVELOPING A CALIBRATION CURVE

In examining the behavior of the RAM-1, target concentrations of 1, 2, 4, and 10 mg/m^3 were arbitrarily selected. The conclusions were based on regressions for data in that concentration range. Extrapolating these regressions to very high concentrations could conceivably lead to very large errors. If the user wishes to make measurements at such high concentrations, he or she should make some comparative measurements at those levels during the calibration procedure.

Since the RAM-1 was tested at concentrations above nominally 1 mg/m^3, little or no meaning was attached to the y intercept of the regression equations. A functional relationship to be used for calibration, however, would be greatly simplified if the y intercept were zero. Therefore, the user, when developing a calibration curve, may wish to perform the regression analysis to force the line through the origin. Many statistics books, including Natrella (13), offer procedures for such a regression.

Before using such a procedure, however, one should be sure that the RAM-1 does indeed indicate zero in dust-free air. Manufacturer data and earlier Bureau data (9) indicate that the RAM-1's zero indication, once adjusted in a dust-free environment, is not affected by temperature, humidity, etc. Background scattering resulting from dust contamination of the optics would cause a zero shift. However, it was found that the clean-air sheath (9) over the optical surfaces successfully prevents deposition of dust. A properly adjusted RAM-1 should, therefore, read 0 mg/m^3 when no dust is present in the air.

Although forcing the regression through zero can be justified, the user should nevertheless make comparison measurements at concentrations near 0 mg/m^3. These measurements would (a) establish linearity in the low concentration range and (b) estimate the precision of the RAM-1 at low concentrations.

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